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Analysis of Data Interruption in an LTE Highway Scenario with Dual Connectivity

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Abstract—This study evaluates whether last versions of Long Term Evolution with dual connectivity are able to support the latency and reliability requirements for the upcoming vehicular use-cases and time-critical applications. Data interruption times during handovers and cell management operations are evaluated by means of system level simulations for a high-speed scenario. The scenario models a highway covered by a macro layer and an ultra dense network of small cells distributed on both sides of the road. Results reveal that for single connectivity, and due to the large amount of handovers, terminals are unable to exchange data with the network about 5 % of the time. This time is considerably reduced if dual connectivity with split bearer architecture is adopted, with less than 1 % of time in data interruption. However, when adopting secondary cell group architecture, the relative data interruption time increases up to 6.9 %.

I. INTRODUCTION

Nowadays, passengers in vehicles tend to consume large amounts of entertainment and media content while commuting [1]. A possible solution to deal with the increasing number of active users along roads, and to increase the capacity, may be the deployment of small cells. This offers several advantages; however, the addition of small cells also comes with some challenges related to efficient mobility management, especially, for users traveling at high speeds [2].

Dual connectivity (DC) is a recently developed feature for Long Term Evolution (LTE) Release-12 [3], which significantly increases the end-user throughput and achieves enhanced mobility robustness [4]. Examples of DC studies include assessments of throughput gains [4]–[6], as well as mobility performance results [2], [7]. The majority of these former studies are conducted for urban scenarios, with the users moving at moderate velocities, and do not study the effects at handovers and cell management events as, for example, data interruption times.

Field measurements of LTE mobility reported in [8], show that each handover results in an average data interruption time of 50 ms. Nevertheless, delays can be larger than 80 ms 5 % of the time. As a result, data interruption times caused by mobility events are becoming an increasing problem that needs special attention, especially, in the highway scenario as handovers and cell management events rates increase with the speed. The majority of broadband applications may be supported by the use of small cells and DC; however, data interruption becomes a potential issue when considering the stringent latency and reliability requirements of the upcoming vehicular use-cases, traffic safety applications and the eventu-

ally migration towards higher degree of autonomous driving [9], [10].

The focus of this paper is, therefore, on the data interruption time caused by handovers and cell management events in a highway scenario. A network topology with an overlay macro layer is assumed, supplemented by small cells along the highway to boost the capacity. Macro and small cells are deployed at separated carrier frequencies using LTE. Cases with and without DC are studied. For DC operations, the performance is analyzed including the two user-plane architectures that the 3rd Generation Partnership Project (3GPP) has defined [11]. As our objective is to present results of high practical relevance, we conduct the analysis for a specific real-life highway segment, which is reproduced in a system level simulator. In addition, latency measurements of the various steps of the handover procedures and cell management actions conducted in [12], are fed into the simulations to have high realism on the assumed parameters.

The rest of the paper is structured as follows: Section II describes the scenario that will be analyzed and the mobility framework. Section III explains the adopted simulation methodology, and Section IV presents the performance results. Finally, Section V concludes with the final remarks and the proposed future work.

II. SCENARIO DESCRIPTION AND MOBILITY FRAMEWORK

The studied scenario is a 7.5 km section of the E-45 highway that encircles the city of Aalborg, Denmark. As illustrated in Figure 1, the scenario is characterized by two network layers operating at separate frequency bands (non co-channel). The LTE macro layer represents the actual network deployment of one of the Danish operators. The small cells layer, on the other hand, is a fictitious Ultra Dense Network (UDN) distributed along the highway.

The macro network is deployed at 1800 MHz and consists of 23 cells, distributed on 13 base station sites, with an average Inter-Site-Distance (ISD) of 1092 m, an average antenna height of 31.3 m and an average tilt (mechanical and electrical) of 2.1°. The small cells layer operates at 3400 MHz with a minimum ISD of 100 m. The small cells are deployed on both sides of the highway to ensure good coverage along the road. In total, there are 119 small cells in the scenario. Table I summarizes additional information about the characteristics of the network.

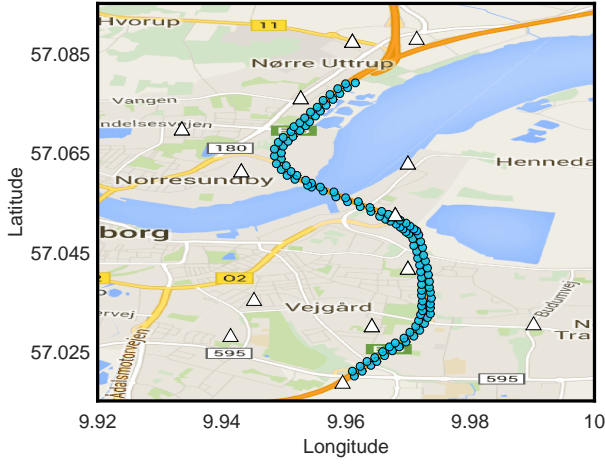


Fig. 1. Illustration of the analyzed highway scenario. Macro sites are depicted as white triangles while small cells are illustrated as blue circles.

This study considers a case with single connectivity User Equipments (UEs) used as a baseline, and another one with all UEs capable of performing DC operations.

A. Mobility with Single Connectivity

In this mode, the UE consumes radio resources from one cell at a time. Following the parametrization in [7], intra- and inter-frequency handovers are triggered by the A3 event (neighboring cell becomes offset better than the serving cell). Intra-frequency events (macro-to-macro and pico-to-pico) are based on the Reference Signal Received Power (RSRP) Radio Resource Management (RRM) measurement while inter-frequency handovers (macro-to-pico or vice-versa) are based on Reference Signal Received Quality (RSRQ).

B. Mobility with Dual Connectivity

In this case, the UE is able to consume radio resources provided by, at least, two different network points [3]. The eNodeB (eNB) that terminates the S1-Mobility Management Entity (MME) interface, acts as the mobility anchor towards the Core Network (CN), and manages the Radio Resource Control (RRC) signaling, is named the Master-eNB (MeNB). The eNB which provides additional radio resources for the UE is defined as Secondary-eNB (SeNB). In this study, it is assumed that a macro cell acts as the MeNB while a small cell plays the role of the SeNB. Moreover, it is also assumed that each UE can be configured with only one SeNB. As recommended in [7], mobility at the macro layer (MeNB handover) is governed by the A3 event, based on the RSRP. A second data link from the small cell layer is added (SeNB addition) if a neighbor small cell becomes better than a certain threshold as the event A4 dictates, based on the RSRQ. The small cell serving the second data link is changed (SeNB change) according to the RSRP A6 event (neighbor small cell becomes offset better than serving small cell). Finally, if the measured RSRQ from the SeNB becomes worse than a certain threshold, as the event A2 states, the additional link is removed (SeNB removal). The use of these mobility events is shown in

TABLE I
NETWORK PARAMETERS

Macro Layer	
Carrier frequency	1800 MHz
Channel bandwidth	20 MHz
Number of cells	23
Number of sites	13
Average antenna height	31.3 m
Antenna height std. deviation	13.22 m
Average antenna tilt	2.1°
Average tilt std. deviation	1.6°
Average ISD	1092 m
Minimum ISD	624 m
Small Cells Layer	
Carrier frequency	3400 MHz
Channel bandwidth	20 MHz
Number of cells	119
Antenna height	5 m (Fixed)
Antenna pattern	Omni-directional
Average ISD	100 m

Figure 2. Notice that in LTE Release-12 any aggregated SeNB should be released before a MeNB handover.

C. User-Plane Architectures for Dual Connectivity

This study considers the two user-plane architectures defined by the 3GPP in [11]. Both architectures are depicted in Figure 3. A detailed comparison between architectures can be found in [3].

- **SCG Bearer Architecture:** In Secondary Cell Group (SCG) bearer the SeNB is connected directly to the CN via S1, allowing the S1-U termination not only at the MeNB, but also at the SeNB. In this architecture, the two eNBs carry different data bearers. Independent Packet Data Convergence Protocol (PDCP) entities are considered at both nodes, and low requirements in the back-haul interface between the MeNB and the SeNB

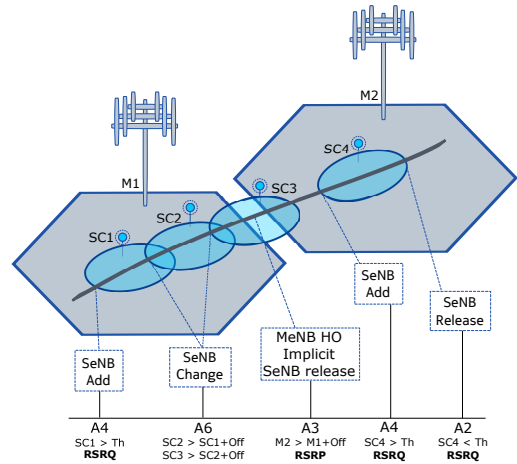


Fig. 2. Mobility events with dual connectivity.

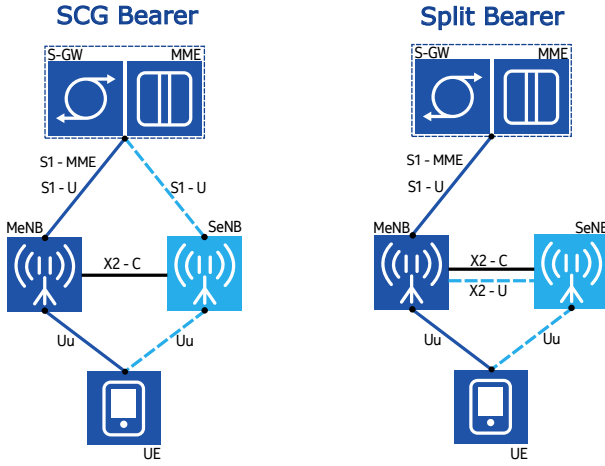


Fig. 3. User-plane architectures for dual connectivity.

are needed. Regarding mobility, SeNB cell management is visible to the CN.

- *Split Bearer Architecture*: In split bearer architecture the data bearer is split into multiple eNBs. In this alternative, the S1-U is terminated at the MeNB, where the PDCP layer resides. All DC traffic should hence be routed, processed and buffered at the MeNB, requiring flow-control and efficient back-haul connection between the MeNB and the SeNB. Unlike the SCG bearer architecture, the SeNB mobility is hidden to the CN and it is not necessary to forward data between SeNBs or to perform a S1 path switch at each SeNB change.

D. Data Interruption Time

During the handover execution phase, the UE interrupts data exchange with the network. Communication is not restored until the handover is completed and the UE receives the first data package from the target cell. Data interruption is experienced at each cell change for single connectivity and at each MeNB handover for DC.

For DC, the interruption of the second link due to SeNB management events depends on the chosen user plane architecture. In SCG bearer architecture, the bearer terminated at the SeNB experiences an interruption at every SeNB change because the path at the Serving Gateway (S-GW) has to be updated. This interruption time can be decreased by allowing data forwarding between the serving and target SeNBs. Nevertheless, it cannot be totally eliminated because of the time it takes to reconfigure the UE. For split bearer architecture, the bearer terminates at the MeNB. As a result, and assuming that there are enough available resources, the MeNB can adapt the scheduled resources to the UE while it performs an SeNB operation hence, compensating the effects of the data interruption. Thus, SeNB management interruption time can be considered close to zero for split bearer.

Measurements reported in [12] characterized the time it takes to exchange signaling messages between nodes, includ-

TABLE II
MOBILITY EVENTS DURATION AND INTERRUPTION TIMES.

	SCG Bearer	Split bearer
Total time - Handover	164 ms	164 ms
Total time - SeNB addition	144 ms	79 ms
Total time - SeNB change	154 ms	89 ms
Total time - SeNB release	117 ms	52 ms
Data interruption time - Handover	42 ms	42 ms
Data interruption time - SeNB addition	37 ms	0 ms
Data interruption time - SeNB change	37 ms	0 ms
Data interruption time - SeNB release	37 ms	0 ms

ing the needed time to process each message and the time it takes to perform a data path update. Using these times and following the signaling flows described in [3] for each mobility event, the interruption times shown in Table II are used. Notice that these are typical average values, and different factors at the network side, e.g. load conditions at the target cell, may increase the interruption times. Additional back-haul delays are not included.

III. SIMULATION METHODOLOGY

Connected-mode mobility performance is evaluated by means of advanced simulations. The system level simulator implements the mobility mechanisms defined by the 3GPP for LTE, including physical-layer measurements, Layer-3 filtering and reporting events. The RSRP, RSRQ and Signal-to-Interference-plus-Noise-Ratio (SINR) for each user are calculated on each time-step, followed by the SINR to throughput mapping estimation. Effects of scheduling, link adaptation, Hybrid-Automatic-Repeat-Request (HARQ) and Multiple-Input and Multiple-Output (MIMO) are included. The tool has been used in several standardization and research studies, such as [7], [12], [13]. More details on the simulator can be found in [14].

A total of 630 users are dropped in the simulations, divided into slow- and high-speed users. Ten slow-speed users per macro area are considered, moving at 3 kmph. Each of the users follow random directions thorough the whole scenario, shown in Figure 1. The purpose of these slow-users is to generate background interference. Additionally, 400 users moving at 130 kmph are dropped along the highway. The stretch of the highway is modeled with two lanes per direction, and each high-speed user is randomly assigned to one lane. Among all simulated users, statistics are only collected from the highway users. All users in the network generate traffic according to a Poisson process.

For the baseline case, a fast transition between small cells is favored by setting a Time-To-Trigger (TTT) of 40 ms. Macro-to-pico handovers are set to a larger TTT to ensure that the signal from the small cells is stable for a longer time, thus avoiding Radio Link Failures (RLFs). For DC simulations, the SeNB events are also set to 40 ms of TTT so that, results can be compared with the baseline case. Moreover, a fast transition between small cells is guaranteed by setting the SeNB change

TABLE III
SIMULATION PARAMETERS.

Transmitted power	Macro: 46 dBm. Pico: 30 dBm
Path loss	Macro: Vehicular test environment [16] Small Cells: Urban Micro (UMi) [17]
Number of UEs	230 free users + 400 highway users
Users speed	Background: 3 kmph. Highway: 130 kmph
Packet call size	Negative exponential distributed. Average: 1 Mbit
Inter-arrival time	Average: 2 s
Sim. Time	210 s
RLF [15]	Qin: -6 dB. Qout: -8 dB. T310: 2 s
Handover / MeNB Changes - A3 event	
Macro-Macro	Offset: 3 dB. RSRP based. TTT: 256 ms
Macro-Pico	Offset: 3 dB. RSRQ based. TTT: 128 ms
Pico-Pico	Offset: 3 dB. RSRP based. TTT: 40 ms
Pico-Macro	Offset: 3 dB. RSRQ based. TTT: 40 ms
Pico RE	6 dB
SeNB Management Events	
SeNB Addition	A4 event. Threshold: -12 dB-RSRQ. TTT: 40 ms
SeNB Change	A6 event. Threshold: 1 dB-RSRP. TTT: 40 ms
SeNB Release	A2 event. Threshold: -17 dB-RSRQ. TTT: 40 ms

offset to 1 dB. Poor secondary links are avoided by setting the SeNB release threshold to -17 dB of RSRQ. Furthermore, a Range Extension (RE) of 6 dB is applied to increase the utilization of the small cells in the highway. To ensure that the users are able to traverse the whole highway stretch, the simulation time is set to 210s. Simulation parameters are summarized in Table III.

The main Key Performance Indicators (KPIs) collected from the simulations are: the number of mobility events, the rate of RLFs, the number of Handover Failures (HOFs) and the data interruption times. The definition of RLF and HOF can be found in [15]. Moreover, the user throughput is also analyzed.

IV. PERFORMANCE RESULTS

Figure 4 shows the number of events and the connectivity distribution that a UE experiences. As can be seen, this scenario is especially challenging due to the large number of mobility events. When using single connectivity, a UE at 130kmph experiences an average of 4176 handovers per hour, corresponding to 1.16 events per second. The device is connected to the small cells 96.6% of the time, where intra-frequency handovers between the small cells dominate the statistics. For DC, the total number of events increases because each UE maintains two active links. However, MeNB handovers are reduced by 83 %, with a total number of 0.2 events per second. In this case, SeNB changes are dominant with 1.3 events per second. The latter is expected because the mobility parametrization of 1 dB offset favors it. On average, a UE is operating in DC 95.7% of the time. No RLFs or HOFs are observed in the simulations for single and dual connectivity.

Figure 5 depicts the data interruption time experienced per UE. For single connectivity, each UE performs an average of

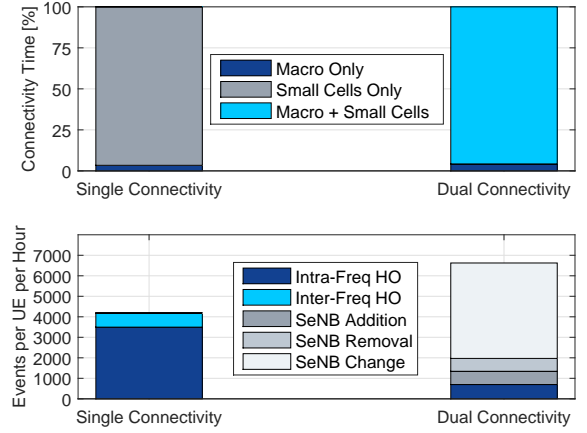


Fig. 4. Connectivity distribution and mobility events for single and dual connectivity modes.

1.16 handovers per second. Considering 42 ms of interruption time per event and a driving time of 210 s, it can be calculated that each UE experiences a total interruption time of 10.2 s. This means that a single connectivity device is not able to transmit or receive any data 4.8 % of the driving time. Notice that when considering 80 ms of interruption time per event, as found in [8], the total data interruption time increases up to 9.3 %, and 11.6 % when considering 100 ms.

For DC, 0.2 MeNB handovers per second occur, resulting in an interruption time of 1.7 s. When SCG bearer architecture is used, the delays at the small cells layer should be added. Since the data bearer terminates at the SeNB, each SeNB management event is affected by the E-UTRAN Radio Access Bearer (E-RAB) modification and the possible delays when the S-GW forwards the data packets towards the eNBs involved. Moreover, due to the large number of SeNB events, SCG bearer adds 12.8 s to the total interruption time. Considering the interruption time due to MeNB handovers and due to SeNB management events, it can be calculated that the UEs are in data interruption for 6.9 % of the time. The contribution of each SeNB event to the interruption time for SCG bearer is depicted in Figure 6. On the other hand, for the split bearer, the delays at each SeNB management event can be neglected and

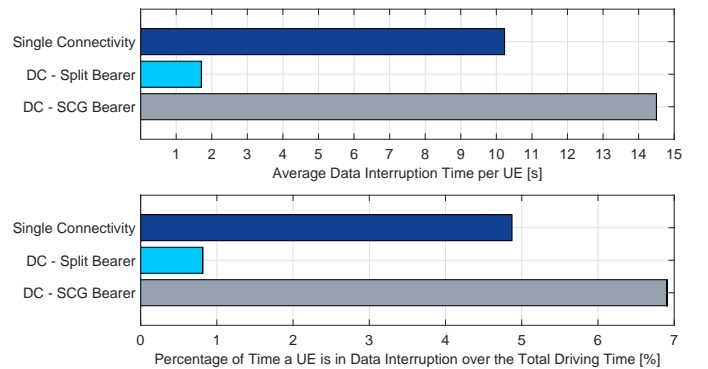


Fig. 5. Data interruption time per UE with single and dual connectivity.

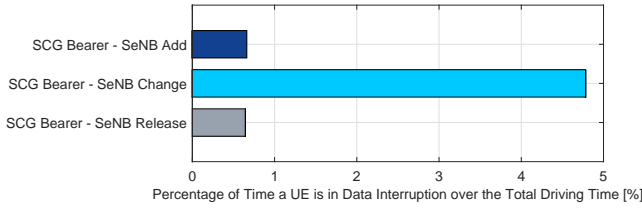


Fig. 6. Percentage of time in data interruption at the small cells layer with SCG bearer architecture for each SeNB management event.

the main contribution to the data interruption time is given by the MeNB handovers, reducing the latency. In other words, for the split bearer, the UEs are in data interruption only 0.81 % of the total time.

Table IV shows one of the main benefits of DC: to improve the per-user throughput. As it can be observed, maintaining two data links increases the average user throughput by 10 %. The major improvement is obtained in the 5-percentile with a gain larger than 16 %. This shows that users experiencing bad radio conditions in a link, can mitigate the effects by aggregating an SeNB hence, increasing their throughput. The average Physical Resource Block (PRB) utilization of the macro cells close to the highway is larger than 70 %, indicating high load conditions. Previous DC studies reported that the achievable throughput gain varies with the load of the network [5], [18]; therefore, under lower offered load, users will perceive larger throughput gains with DC.

TABLE IV
HIGHWAY USERS THROUGHPUT FOR SINGLE AND DUAL CONNECTIVITY.

	Single connectivity	Dual connectivity	Gain
Average	15.6 Mbps	17.3 Mbps	+ 10.9 %
5-percentile	617 Kbps	717 Kbps	+ 16.2 %
50-percentile	10.7 Mbps	11.9 Mbps	+ 11.8 %
95-percentile	46.9 Mbps	51.8 Mbps	+ 10.5 %

In general, results show how DC is able to reduce the overall experienced data interruption time. In real implementations, the interruption times will lay in between the presented numbers. For example, data forwarding between nodes may not always be available, resulting in larger delays for split bearer. On the other hand, results for SCG can be improved with some mobility enhancement techniques –like preparing cells as the UE moves along the highway to anticipate the mobility events and forward data towards the target cells– reducing the interruption times. Nonetheless, the presented numbers show that the improvement provided by split bearer may not be sufficient to deal with the 5 ms end-to-end latency required by the vehicular use-cases envisioned for the next generation of mobile networks [10]. Additionally, the cost in terms of signaling is also becoming a potential issue as the users experience a large number of mobility events.

V. CONCLUSIONS

Mobility performance in a LTE highway scenario with and without dual connectivity is studied by means of extensive

system level simulations. Results reveal how, with single connectivity, the UEs are unable to receive or transmit any data about the 5 % of the time due to handovers. Dual connectivity significantly reduces the interruption time depending on the chosen architecture. By adopting the split bearer user-plane architecture, the devices experience data interruption only 0.81 % of the time. Nevertheless, results show that the improvement is not sufficient to deal with the latency requirements demanded by the new vehicular use-cases.

As future work, it is recommended to investigate solutions to reduce the interruption time and the signaling load towards fulfilling the requirements imposed by the envisioned use-cases for the next generation of mobile networks.

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